Magnetic resonance angiography minimizes need for arteriography after inadequate carotid duplex ultrasound scanning

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Purpose: **We prospectively evaluated whether magnetic resonance angiography (MRA) enabled definition of cerebrovascular anatomy after indeterminate or inadequate results at duplex ultrasound scanning to facilitate patient selection for carotid endarterectomy (CEA) and for technical planning.**

Methods: **After implementation of a protocol in October 1998 to minimize use of cerebral arteriography, MRA (arch/cervical two-dimensional and cranial three-dimensional time of flight technique) was performed in 138 consecutive patients with cerebrovascular occlusive disease and inconclusive duplex scans obtained by an ICAVL-approved laboratory. The ability of MRA to define anatomic features unresolved at duplex scanning was compared between categories of duplex scan inadequacies. Operative outcome was compared between patients requiring MRA before CEA (n = 66) and a concurrent cohort undergoing CEA on the basis of duplex scan results only (n = 69).**

Results: **Incomplete imaging of the carotid bifurcation, because of high bifurcation, long (>3 cm) internal carotid artery (ICA) plaque, or calcific shadows, was the most common reason for inadequate duplex scans (n = 74, 53%), followed by borderline severe ICA disease (23.17%), suspected extracervical disease (supra-aortic trunk, vertebral, or intracranial, 22, 16%), ICA near- occlusion (12.9%), and diffuse recurrent stenosis (7.5%). MRA enabled resolution of duplex scan inadequacies in 95% of patients with disease confined to the carotid bifurcation, and 90% of all patients, but was least accurate for delineation of extracervical lesions (77%) and near-occlusions (75%). In 5 of 8 patients (6%) arteriography was performed to determine operability of ICA near-occlusion or extracervical lesions. Combined stroke and death rates after CEA were not statistically different (*P* = .3) between patients requiring MRA (3 of 66, 4.6%) and the concurrent group in whom MRA was performed solely on the basis of duplex results (1 of 69, 1.5%). However, intraoperative technical adjustments (anatomy that precluded shunt use, extended endarterectomy length, ICA shortening due to tortuosity) were planned in 71% of patients (12 of 17) with MRA-defined anatomy, but only 36% of patients (4 of 11) with long CEA on the basis of duplex results only (*P* = .08).**

Conclusion: **MRA replaces the need for cerebral arteriography in most patients after inadequate carotid duplex scanning. Delineation of cerebrovascular anatomy at MRA assists in determination of CEA candidacy and operative planning. (J Vasc Surg 2003;38:422-31.)**

Over the past decade duplex ultrasound scanning has become the preferred imaging method for evaluation of suspected cerebrovascular occlusive disease and for aiding patient selection for carotid endarterectomy (CEA).[1] Because duplex scanning enables accurate grading of severity of carotid bifurcation and internal carotid artery (ICA) disease in nearly 90% of patients, clinical management is infrequently altered as a result of routinely performed cerebral arteriography.[2-5] Use of arteriography is justified when there is incomplete ultrasound scanning of the cervical region and as a complementary study where findings at duplex scanning are inconclusive or equivocal. Operative candidacy is determined not only by accurate grading of ICA disease but also by operability of the lesion. Surgical accessibility, extent of lesion, and need for technical adjustments because of adverse anatomy all influence the relative degree of operative difficulty and may negatively affect a narrow risk-benefit advantage in some patients at high risk. Other than the study by Wain et al,[6] little attention has been focused on the ability of duplex scanning to image complex ICA anatomy before CEA. Furthermore, differentiating technically adequate from indeterminate duplex scans is subjective, is not standardized, and varies between centers. Specific criteria defining an inadequate carotid duplex scan with reference to anatomic information necessary for patient selection and CEA planning are lacking.

Evolving experience with magnetic resonance angiography (MRA) has generally been favorable, with reported accuracy greater than 80% for grading severity of carotid occlusive disease with two-dimensional (2-D) or three-dimensional (3-D) time-of-flight (TOF) or phase-contrast techniques.[7-10] During an angiographic validation period from 1996 to 1998 at our affiliated Veterans Affairs hospital, MRA demonstrated 98% accuracy for detection of ICA

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Table I. Duplex scan-derived threshold velocities and corresponding MRA criteria for grading severity of ICA occlusive disease validated at University of South Florida[11,12]

ICA stenosis (%)	*Duplex scanning criteria*	*MRA criteria*
<50	PSV < 125 cm/s ICA-CCA ratio < 2	<50% stenosis
50-74	PSV > 125 cm/s EDV < 125 cm/s 2 < ICA-CCA ratio < 4	50-74% stenosis or short (<3 cm) flow gap
75-99	EDV > 125 cm/s ICA-CCA ratio > 4	75-99 % stenosis or flow gap (<6 cm)
Occlusion	No ICA flow CCA EDV = 0	No cervical or intracranial ICA signal

MRA, magnetic resonance angiography; *ICA,* internal carotid artery; *PSV,* peak systolic velocity; *EDV*, end-diastolic velocity; *CCA,* common carotid artery.

stenosis greater than 50% and 89% for identification of stenosis greater than 75%.[11] We recommended adjunctive use of MRA to corroborate disease severity and facilitate patient selection for CEA after equivocal duplex scan results. We then initiated a prospective evaluation of the ability of MRA to image cerebrovascular anatomy necessary for selecting appropriate therapy and safe planning of CEA. The current study sought to determine whether MRA could replace cerebral arteriography as the preferred secondary imaging method after inadequate or inconclusive carotid duplex scanning.

METHODS

We implemented a clinical algorithm in October 1998 at the James A. Haley Veterans Hospital, Tampa, Fla, to minimize use of cerebral arteriography in patients with cerebrovascular occlusive disease. Carotid duplex scanning was the initial imaging method in patients with suspected carotid artery or posterior circulation disease. In most patients appropriate clinical management (operative or medical) was chosen on the basis of duplex scanning results, presence of neurologic or ocular symptoms, and selective use of cranial imaging (computed tomorgraphy or magnetic resonance imaging [MRI]). Carotid MRA was the preferred secondary imaging study after inadequate or indeterminate duplex scanning. Cerebral arteriography was performed only after inconclusive MRA findings, to resolve operability of lesions and to facilitate technical planning. Angioplasty or stenting of the carotid or supra-aortic trunk vessels was performed infrequently, and the required arteriograms to determine endovascular candidacy were excluded from the imaging algorithm and the current study.

All carotid duplex scanning was performed by registered vascular technologists using HDI color-flow scanners (Phillips/Advanced Technology Laboratories, Bothell, Wash) in an ICAVL (Intersocietal Commission for the Accreditation of Vascular Laboratories)–approved, noninvasive laboratory. Cerebrovascular testing included brachial pressure measurements and duplex scanning of carotid, subclavian, and proximal vertebral arteries. When possible, contiguous B-mode and color-flow imaging from the proximal common carotid artery (CCA) to the most distal ICA was performed to assess disease distribution and plaque architecture, and midstream spectral waveforms were recorded at multiple sites. The distance from the carotid bifurcation flow divider to the angle of the mandible was measured on the cervical skin with a method similar to that used by Wain et al.[6] The length of stenotic plaque in the ICA was measured on sagittal images from the bifurcation flow divider to the distal end point of observed mural disease and return of ICA peak systolic velocity to less than 125 cm/s. Angulation of more than 60 degrees between the proximal and distal ICA on sagittal images defined redundancy or kinking. A small diameter distal ICA was defined by luminal width 3 mm or less on the duplex scan, which could preclude carotid shunt placement and mandate vein patching. Technical adequacy of the study was judged and results were interpreted by a single reader (M.R.B.). Grading of severity of ICA occlusive disease was performed according to our previously published threshold velocity criteria[11,12] (Table I). Specific anatomic factors responsible for an inadequate or indeterminate duplex scan (Table II) were arbitrarily categorized as incomplete bifur-

Table II. Specific anatomic criteria and categories defining inadequate or indeterminate carotid duplex scan

Incomplete imaging of carotid bifurcation and cervical region
Deep anatomy and excessive ultrasound beam attenuation
Extensive calcific shadowing (>1.5 cm ICA length)
High carotid bifurcation (<1.5 cm between bifurcation and mandibular angle, and <2 cm ICA imaged above bifurcation)
Long ICA plaque (ICA stenosis >3 cm length above bifurcation, and persistent PSV >125 cm/s in distal ICA)
Small ICA diameter (distal ICA luminal diameter ≤3 mm)
ICA redundancy, kink, coil (precluding complete distal ICA imaging or accurate Doppler insonation with ≤60-degree angle)
Suspected extracervical occlusive disease
Proximal CCA or innominate disease (blunted, low PSV CCA waveform and <75% bifurcation stenosis, or proximal CCA PSV >125 cm/s with local peak velocity ratio >2)
Posterior circulation, subclavian, vertebral disease (brachial pressure difference >15 mm Hg, subclavian or vertebral PSV >250 cm/s, or blunted, low PSV vertebral waveform)
Distal or intracranial ICA disease (blunted, low PSV ICA waveform and <75% bifurcation stenosis)
Borderline or equivocal ICA disease severity
~50% ICA stenosis with symptoms
~75% ICA stenosis without asymptomatic
Carotid near-occlusion
Differentiation between ICA occlusion and >95% stenosis: (low PSV "trickle" flow in ICA)
Diffuse, recurrent carotid stenosis
Long length (>5 cm) or multiple sites of residual or recurrent stenosis after previous carotid endarterectomy

ICA, Internal carotid artery; *PSV,* peak systolic velocity; *CCA,* common carotid artery.

cation or cervical imaging, suspected extracervical disease (supra-aortic trunk, vertebral or intracranial ICA), borderline or equivocal ICA disease severity (complicating management decisions in patients at high operative risk), carotid near-occlusion (unresolved ICA patency and lesion operability), and incomplete imaging of diffuse recurrent carotid stenosis. Secondary imaging studies were not routinely performed because of focal recurrent stenosis, and repeat CEA was planned solely on the basis of the duplex scan in 2 patients.

After inconclusive carotid duplex scanning, MRA was performed with a 1.5 T magnet (Picker Edge, Cleveland, Ohio), with an extracranial 2-D and cranial 3-D TOF technique. As described during our validation study,[11] an extended field of view from the aortic arch to the carotid siphon was evaluated with multiple axial (155), thin (2.6 mm thick), overlapping (1 mm) sections. To optimize cervical arterial resolution, short repetition time (30 ms) and echo time (7.4 ms) in the gradient echo pulse sequence were chosen, and caudally directed venous signals were suppressed. 3-D reconstruction of major extracranial and intracranial arteries was accomplished from axial source images with a maximum intensity pixel projection ray tracing technique, and could be viewed as 12 longitudinal images rotated at 15-degree increments. Gadolinium enhancement has not improved MRA carotid image resolution in our experience, because of inability to avert overlapping venous signals and despite timing adjustments in contrast injection and image sequencing. Cranial MRI was performed along with MRA only when hemispheric symptoms were present and ischemic infarction was suspected. MRA images were interpreted by one author (M.R.B.) according to established criteria for disease severity[11] (Table I). ICA stenosis was measured as percent diameter reduction, with the North American Symptomatic Carotid Endarterectomy Trial (NASCET) method, and the maximal degree of stenosis was identified from the multiple rotated carotid MRA images. Presence of a signal void or flow gap in the proximal ICA, with contiguous flow signal in the distal and intracranial ICA, correlated with 60% or greater stenosis at arteriography in our previous experience,[11] and was noted in either 50% to 74% or 75% to 99% disease categories detected at duplex scanning (Table I). Length of ICA stenosis (or flow gap) was determined with magnified images and internal MRA distance calibrations. In cases of suspected high bifurcation, the position of the proximal ICA stenosis could be estimated relative to cervical vertebral level from axial source images (high, above C3). Concordance (or discordance) of MRA and duplex scanning results for grading severity of ICA occlusive disease were recorded per patient for the carotid system or vessel side with inconclusive duplex scans. The ability of MRA to define anatomic features unresolved at duplex scanning and to facilitate decisions regarding operative candidacy, technical planning, and medical management was determined. Multiplanar arch and cerebral contrast arteriography, when necessary after inconclusive MRA findings, was performed with and without subtraction techniques in an angiographic suite, using a Multistar Top system (Siemens, Iselin, NJ).

CEA was recommended to treat ICA stenosis greater than 50%, recent (<6 mo) ipsilateral hemispheric or retinal symptoms,[13] or stenosis greater than 75% in patients with acceptable operative risk and without neurologic symptoms. General anesthetic was administered, and procedures were performed through a longitudinal skin incision with routine use of a temporary carotid shunt, conventional endarterectomy technique, prosthetic or vein patch closure, and intraoperative completion duplex scanning. Thirty-day perioperative outcome in patients undergoing CEA after MRA and inadequate duplex scanning was compared with that in a concurrent group undergoing CEA solely on the basis of a technically adequate carotid duplex scan. Comparisons were also made between these groups with respect to incidence of perceived higher risk CEA (presence of symptoms, repeat CEA, combined CEA and coronary artery bypass grafting, concomitant vertebral or proximal vessel reconstruction), need for intraoperative technical adjustments (alteration of operative exposure, inability to place the carotid shunt, extended length of endarterectomy [>7 cm]), ICA resection or shortening due to redundancy, kinking, or coil), and whether adjustments were preoperatively planned on the basis of carotid imaging studies. If difficulty with shunt placement was anticipated from preoperative imaging (small distal ICA, significant redundancy), adjunctive electroencephalographic monitoring was used during CEA.

Statistical analysis. Comparison between categories of duplex scan inadequacies with respect to concordance of MRA and duplex findings and the relative ability of MRA to resolve inconclusive duplex findings were determined with χ^2 analysis (Table III). Categorical variables were compared with χ^2 analysis and the Student *t* test for continuous variables pertaining to MRA and duplex-only CEA groups (Table IV). All data are reported per patient. $P \geq .05$ was considered statistically significant. Continuous variables are expressed as mean ± SD.

RESULTS

Cerebrovascular evaluation. Between October 1998 and July 2002, 3746 carotid duplex studies, on average, 83 per month, were performed in our noninvasive vascular laboratory. For 143 patients (3.8%) duplex scans were deemed inadequate, precluding clinical decision-making (Fig 1). Only 5 of these patients (3.5%) were excluded from MRA, because of preexisting cardiac pacemaker (n = 3), severe obesity (n = 1), or intolerable claustrophobia (n = 1). Of the remaining 138 patients undergoing carotid MRA, 5 were women (2%), 73 had symptoms (53%), and mean age was 69 ± 9 years.

Results of MRA in these 138 patients listed are listed in Table III according to category of duplex scan inadequacy. Incomplete imaging of the carotid bifurcation and cervical region accounted for most (53%) inadequate duplex scans, and was due to long ICA stenotic plaque (= 39) (Fig 2) or extensive calcific shadowing of the bulb and ICA (n = 22)

Table III. Incidence of inconclusive findings on duplex scan by category, concordance between duplex scanning and MRA for grading severity of ICA occlusive disease, relative ability of MRA to resolve inconclusive duplex anatomy, and number of cerebral arteriograms required

	# Patients (%)		*Concordance, duplex scan/ MRA*†‡		*Conclusive MRA*§‖		
*Duplex inadequacy category**	*n*	*%*	*n*	*%*	*n*	*%*	*No. of angiograms*
Incomplete cervical imaging	74	53	63	85	70	95	1
Borderline ICA disease	23	17	22	96	22	96	1
Extracervical disease	22	16	18	82	17	77	2
Near-occlusion	12	9	11	92	9	75	3
Recurrent stenosis	7	5	5	71	6	86	1

ICA, Internal carotid artery; *MRA,* magnetic resonance angiography.
*Percentage of all MRA.
†Percentage of patients within category with concordant duplex scans and MRA.
‡No difference between groups; $P = .42$.
§Percentage of patients within category with conclusive MRA.
‖Significant difference between groups; $P = .05$.

Table IV. Comparison between patients undergoing CEA after MRA imaging and inadequate duplex and concurrent operative group based on duplex scanning alone

	MRA group (n = 66)		*Duplex scanning only group (n = 69)*		
Variable	*n*	*%*	*n*	*%*	*P*
Age (y)	68 ± 9		66 ± 9		.95
Diabetes	14	21	23	33	.13
Symptomatic disease	38	58	25	36	.02*
Higher risk CEA (repeat, with CABG, with vertebral reconstruction)	6	9	6	9	.92
Intraoperative technical adjustment	17	26	11	16	.17
Percent planned adjustment	12/17	71	4/11	36	.08
Procedural morbidity	11	17	4	6	.04*
Stroke or death	3	4.6	1	1.5	.3

CEA, Carotid endarterectomy; *MRA,* magnetic resonance angiography; *CABG,* coronary artery bypass grafting.
*Significant difference between operative groups.

in most patients. The percentage of patients with these anatomic features and diabetes (23%) was not higher than the prevalence of diabetes in the entire MRA group (22%), suggesting lack of significant influence of diabetes on extent and calcific content of carotid atherosclerosis. MRA and duplex results were concordant for grading severity of ICA disease in 86% of patients, and did not differ significantly between categories of duplex inadequacy ($P = .42$). ICA stenosis was equally distributed between 75% to 99% and 50% to 74% duplex scanning–detected disease classes for patients requiring MRA. Overall, MRA was conclusive in resolving duplex imaging inadequacies in 90% of patients (n = 124), with 60 patients subsequently undergoing CEA and 64 receiving medical treatment (Fig 1). However, there was significant variation in ability of MRA to resolve cerebrovascular anatomy between categories of duplex scan inadequacy ($P = .05$). While MRA was able to resolve anatomy confined to the cervical carotid artery (incomplete duplex scanning of the bifurcation, borderline ICA disease) in 95% of patients, suspected extracervical lesion (Fig 3) and ICA near-occlusion (Fig 4) were fully delineated in only 77% and 75% of patients, respectively. For suspected extracervical disease, proximal CCA or innominate artery anatomy was resolved at MRA in 13 of 15 patients (87%), compared with distal cervical or intracranial ICA or posterior circulation anatomy in 4 of 7 patients (57%). Portions of the cervical field of view contained image artifacts caused by patient motion or metallic implant interference in 9 patients (6.5%), but none of these resulted in inability of MRA to resolve duplex scan inadequacies. MRA also identified incidental intracranial aneurysms involving the circle of Willis in 2 patients (1.5%).

Cerebral arteriography was necessary in 8 patients after inconclusive MRA (Table III) and in an additional patient with symptoms with an inadequate duplex scan but unable to undergo MRA because of presence of a pacemaker. Arteriography was therefore performed in 6.3% (9 of 143) of patients with inadequate duplex scans and in only 0.2% of all patients initially evaluated with carotid duplex scanning. Five of the eight arteriograms were obtained after inconclusive MRA because of extracervical disease (n = 2) or ICA near-occlusion (n = 3). Extracervical lesions requiring

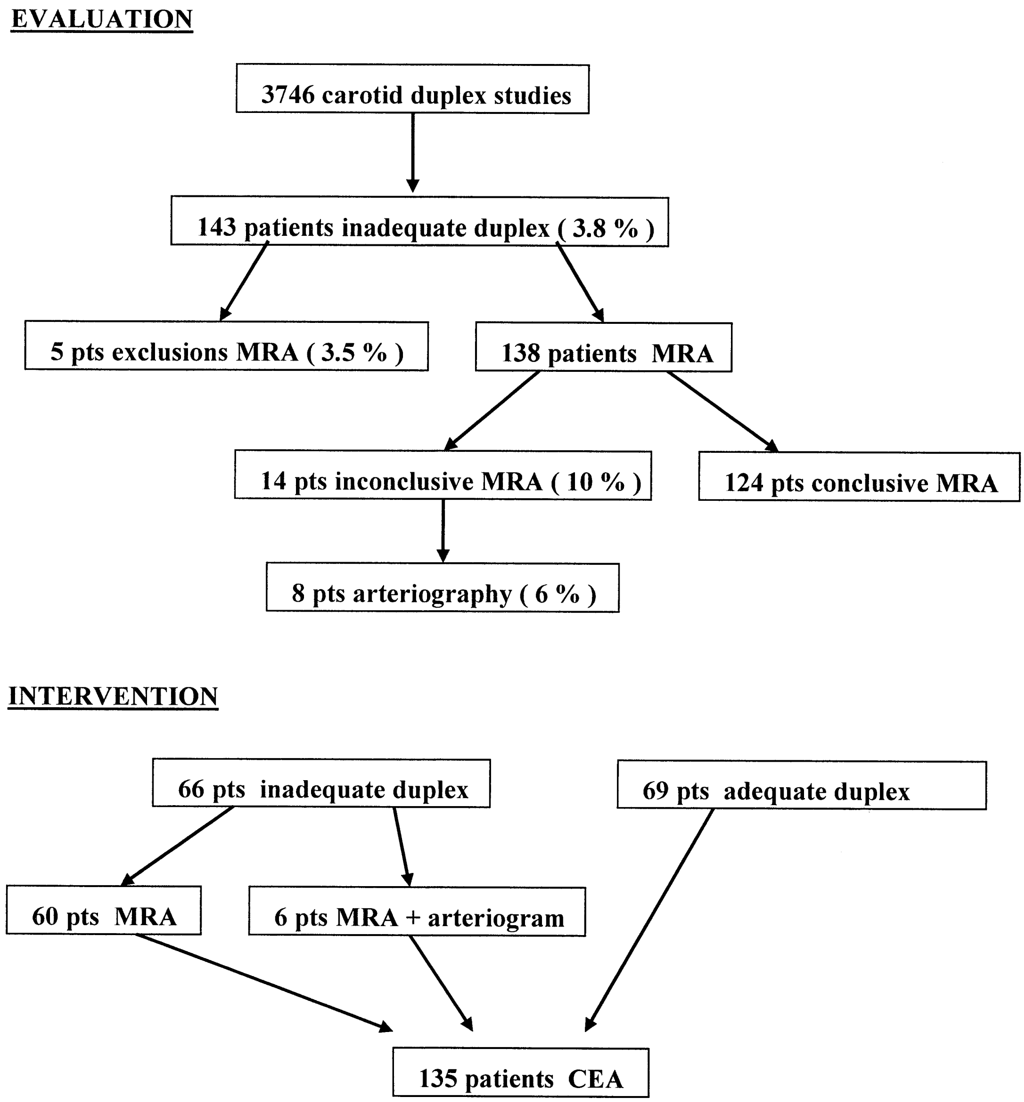

Fig 1. Results of cerebrovascular imaging algorithm, October 1998 to July 2002, for evaluating patients with suspected disease. Resulting intervention (CEA) and required preoperative imaging. *CEA,* Carotid endarterectomy; *MRA,* magnetic resonance angiography.

arteriography included incomplete MRA in the carotid siphon in a patient with suspected tandem stenoses and an unresolved vertebral origin stenosis that required transposition to the CCA and concomitant bifurcation endarterectomy because of anterior and posterior circulation symptoms (Fig 3). Despite consistent concordance between MRA and duplex scanning for differentiating ICA patency from occlusion and determining candidacy for CEA, MRA was unable to delineate distal ICA anatomy to resolve operability in 3 patients with near-occlusion. No patient had procedural complications, and 6 of 8 patients subsequently underwent CEA after cerebral arteriography. Arteriography was not performed after inconclusive MRA of the cervical region (n = 3) and extracervical lesions (n = 3), because these 6 patients without symptoms were considered at unfavorable medical risk for CEA.

Carotid interventions. During the study (Oct 1998–July 2002), 135 patients underwent CEA (Fig 1). Only 4.4% of patients undergoing CEA required arteriography preoperatively. Patients undergoing CEA after MRA and inadequate duplex scanning (n = 66) were similar in age but more commonly had symptomatic disease, compared with those undergoing surgery solely on the basis of duplex scan findings (n = 69) (Table IV). Procedures associated with higher operative risk, including interventions to treat recurrent stenosis (n = 5), combined CEA and coronary artery bypass grafting (n = 6), and CEA combined with vertebral reconstruction (n = 1), were similarly distributed

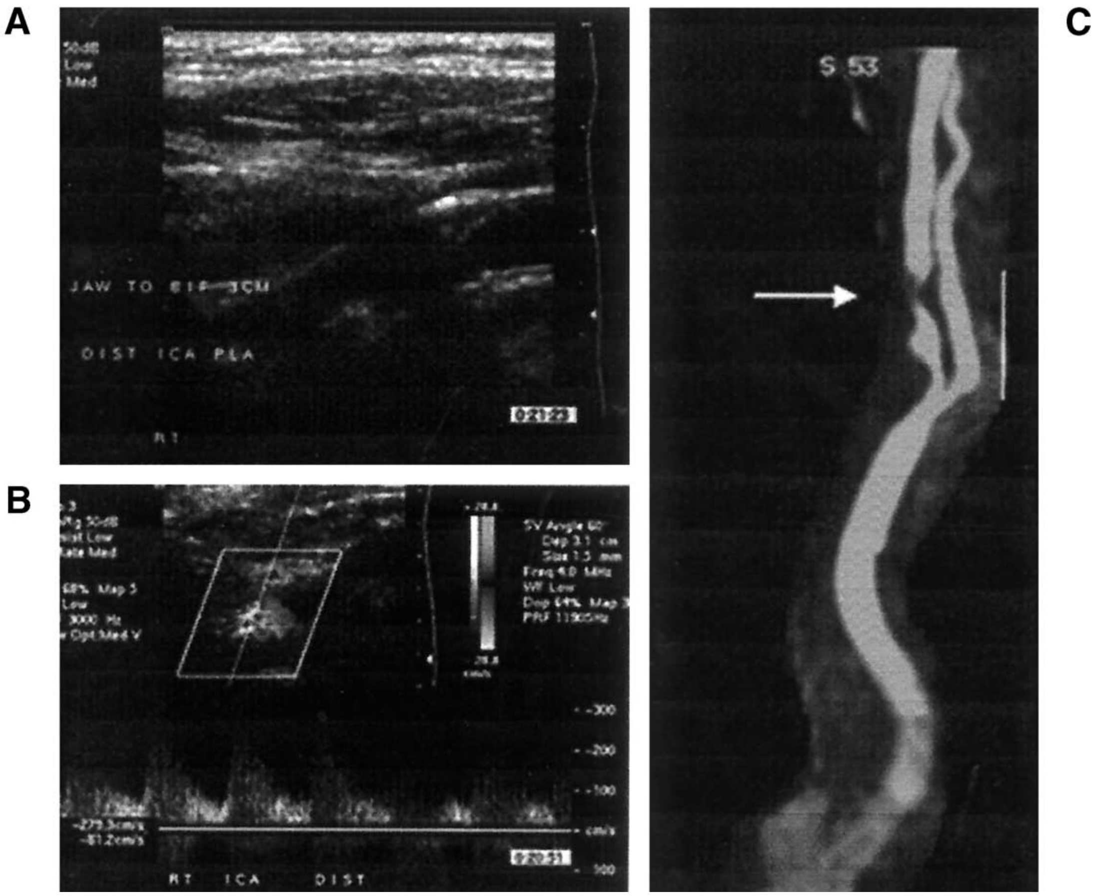

Fig 2. A, Long (3 cm) internal carotid artery (ICA) plaque, with inability to image past stenosis with duplex scanning (persistent ICA peak systolic velocity (PSV) >125 cm/s). **B,** Maximum ICA PSV consistent with greater than 75% stenosis. **C,** Magnetic resonance angiogram shows long stenosis (3 cm by calibration) with short ICA flow gap (*arrow*).

between MRA and duplex scanning only groups. Intraoperative technical adjustments were required in 21% of all CEA, and included inability to place a carotid shunt (n = 8), extended endarterectomy length (n = 8), ICA resection and shortening due to redundancy (n = 8), and altered operative exposure (n = 4). Technical adjustments were more frequently performed in the MRA group, but not to a significant degree. Just over half of operative adjustments were planned on the basis of preoperative images, but a higher percentage of adjustments were planned after MRA imaging (71%) compared with CEA performed on the basis of duplex scans only (36%). Procedure-related complications after CEA included ipsilateral stroke (n = 3, 2.2%), cervical wound hematoma (n = 5, 3.7%), transient cranial nerve injury (n = 4, 3.0%), and difficult postoperative blood pressure control (n = 2, 1.5%). One patient (MRA group) died as a consequence of a motor vehicle accident within 30 days of CEA. Overall procedural morbidity and mortality were higher in patients after MRA imaging than in CEA performed after duplex scanning only. However, the combined ipsilateral stroke and death rate was not significantly greater in the MRA group compared with the duplex scanning only group.

DISCUSSION

Our experience confirms the infrequent need for secondary cerebrovascular imaging and supports reliance on carefully done, technically adequate carotid duplex scanning to aid in clinical management and selection of patients for safe performance of CEA. A low incidence of adverse outcome occurred after CEA performed solely on the basis of preoperative duplex scans, including 20% of cases involving more complex carotid anatomy (recurrent stenosis or necessity of intraoperative technical adjustments). We have also proposed specific criteria for defining an inadequate or inconclusive carotid duplex scan that may be useful in clinical practice. These criteria determined the need for secondary imaging methods to resolve cerebrovascular anatomy and assist therapeutic decisions and CEA planning in the current study. It was not surprising that more than half of patients with inadequate duplex scans had unresolved anatomy in the disease- predisposed bifurcation

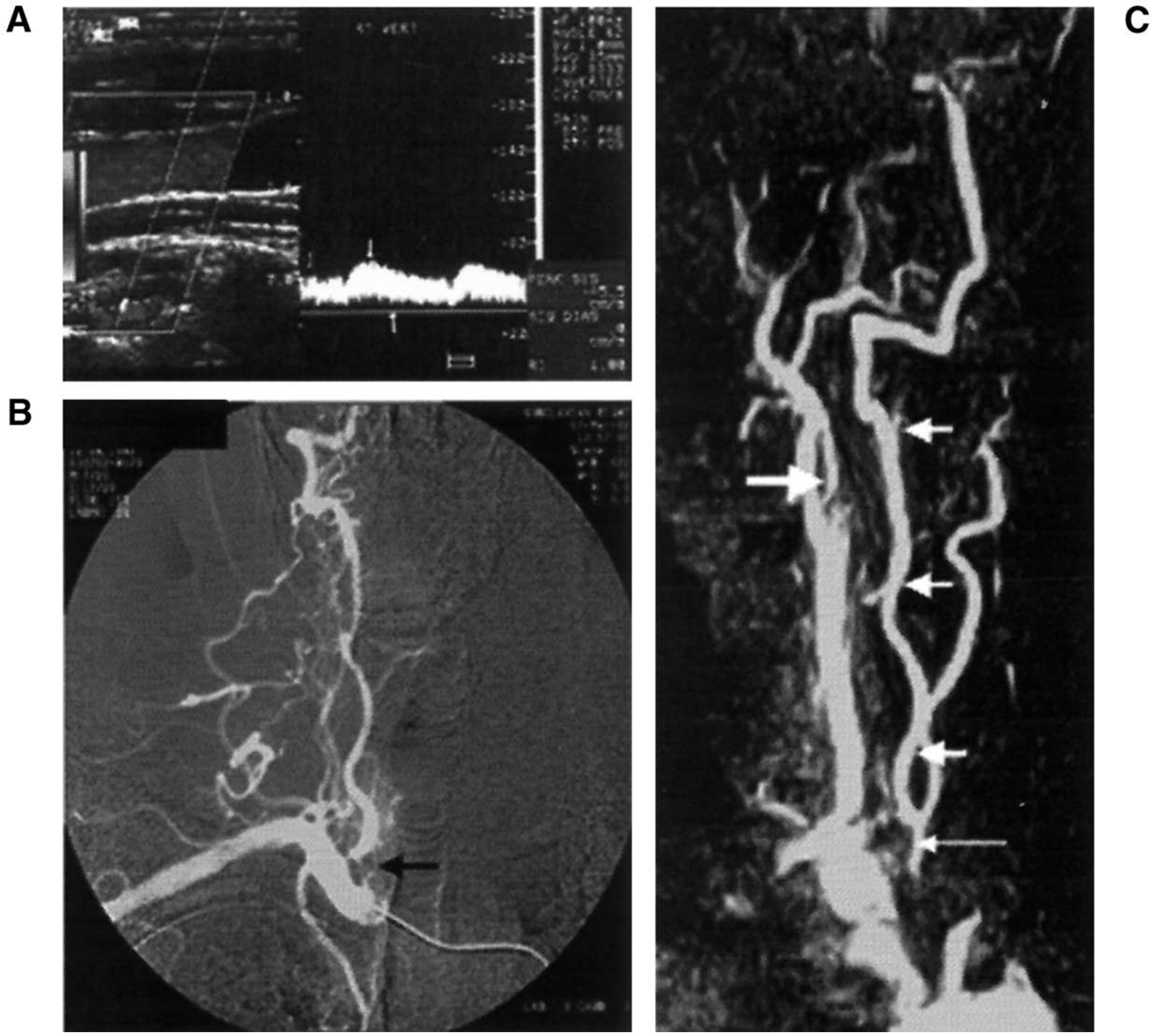

Fig 3. A, Blunted, low peak systolic velocity (46 cm/s) right vertebral waveform at duplex scanning. **B,** Arteriogram exhibits high-grade vertebral origin stenosis (*black arrow*) and thyrocervical trunk collateral vessels. **C,** Magnetic resonance angiogram shows right internal carotid artery occlusion (*large arrow on left*) and patent vertebral artery (*short arrows on right*), but unresolved vertebral origin region (*thin arrow on right*).

region. Strict reliance on these duplex criteria to define inadequate images contributed to the relatively high percentage (nearly 50%) of study patients undergoing MRA before CEA. However, with more liberal reliance on duplex scanning to resolve complex cervical anatomy (Table II), the number of CEA performed without secondary imaging would be expected to decrease. Since the study focused on MRA capability, it was not designed to specifically analyze duplex scanning ability to delineate complex cervical anatomy and its effect on unanticipated intraoperative adjustments. Use of MRA as the secondary imaging study resolved duplex scan inadequacies in 90% of patients, and only 6% of patients required cerebral arteriography to determine lesion operability and to facilitate technical planning. MRA was performed with a commercially available TOF technique without gadolinium enhancement, with several adjuncts (see Methods) to optimize arterial imaging, and were easily interpreted by a vascular surgeon. Only a small number (3.5%) of patients were excluded from MRA, because of an existing pacemaker or severe claustrophobia. It remains to be seen whether carotid image resolution can be preserved in open MRA studies performed in patients with claustrophobia. Image artifact occurred infrequently during MRA, and did not affect study quality or ability to resolve cerebrovascular anatomy. MRA and duplex scanning results were concordant for grading severity of ICA disease in 86% of patients, and approached the accuracy range of our earlier experience,[11] despite the compromised duplex scanning in this study. The tendency with MRA of stenosis "overestimation" related to maxi-

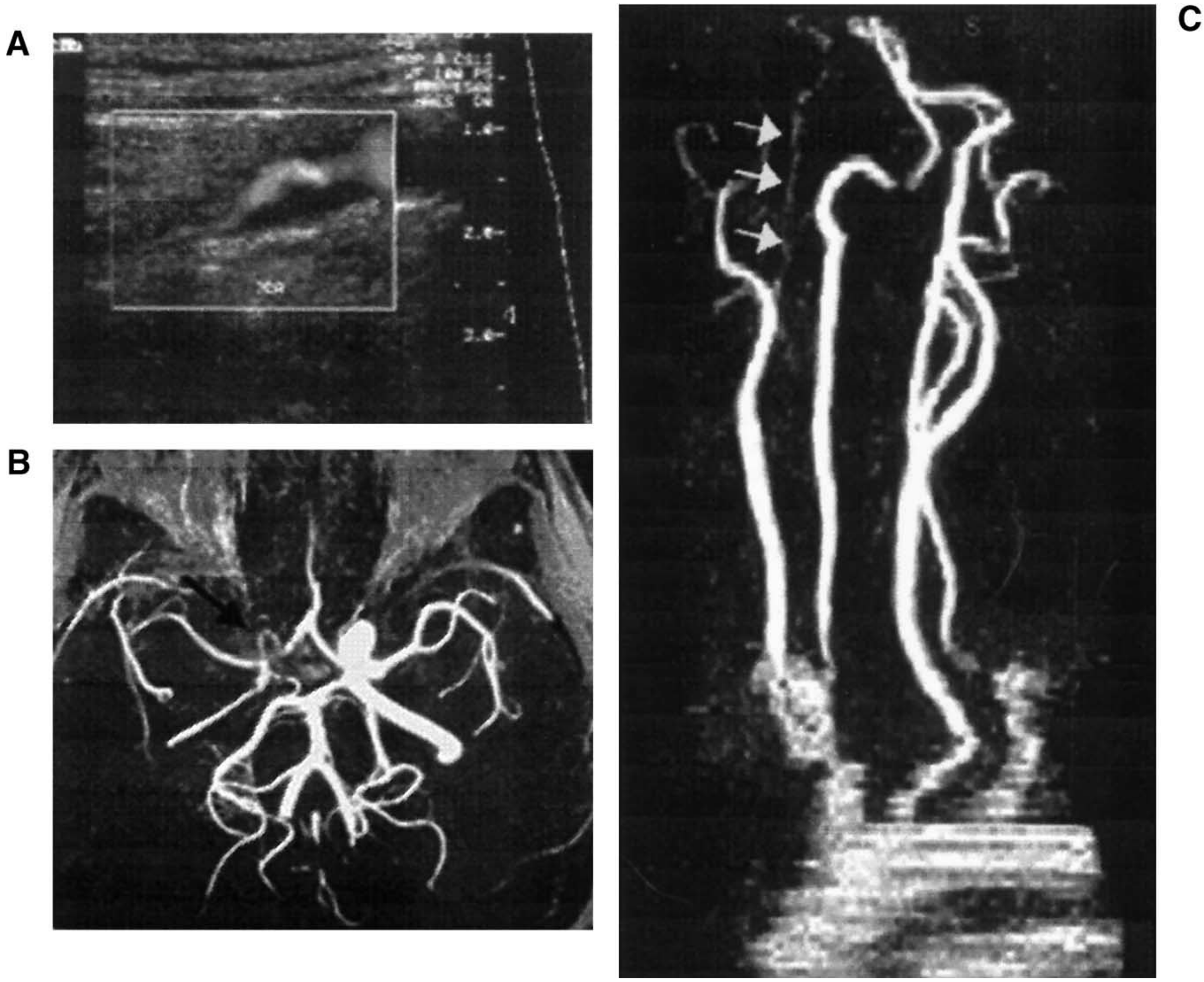

Fig 4. A, Right carotid near-occlusion seen on power Doppler scan. Maximum internal carotid artery (ICA) peak systolic velocity is consistent with greater than 50% stenosis. Note small diameter distal ICA lumen. Magnetic resonance angiograms show intracranial ICA flow signal (*arrow*, **B**) and faint cervical ICA flow signal (*arrows*, **C**), consistent with "trickle" flow.

mum intensity pixel reconstruction techniques, noted by others,[8,14,15] has been explained with better understanding of the hemodynamic causes responsible for MRA signal loss and flow gap formation[16,17] and accurate measurement of maximal stenosis from equivalent rotational projections between MRA and arteriography.[10] Overestimation of lesion severity was not found in our initial MRA-angiographic validation experience,[11] and did not occur when results at MRA were compared with those at duplex scanning or arteriography in this study. Despite increasing interest in gadolinium enhancement, significant procedural MRA technical adjustments are necessary, and imaging validation for accuracy of disease classification remains in the early stages.[14]

Further comment on MRA capability relative to the proposed categories of duplex scan inadequacy is warranted. MRA was most able to resolve anatomy in the cervical carotid region, and virtually eliminated the need for arteriography (1 of 74 patients) after incomplete bifurcation imaging with duplex scanning. MRA reliably differentiated focal from long ($\geq$3 cm) ICA stenosis (Fig 2), location of stenosis relative to the bifurcation, degree of ICA tortuosity, and distal ICA lumen caliber. Each of these factors has technical implications for safe performance of CEA and influences lesion operability. Disease categorization of ICA stenosis was corroborated with MRA after borderline or equivocal duplex scanning results (22 of 23 patients), and arteriography further delineated a suspected bulb ulceration responsible for recalcitrant cerebral embolic episodes in 1 patient at high risk. However, anatomic resolution at MRA was less conclusive for extracervical lesions (77%) and ICA near-occlusions (75%). While MRA imaging of the proximal CCA or innominate vessels was adequate (87% conclusive) with an extended field of view that included the arch, distal ICA-siphon and subclavian-vertebral origin images were less optimal, and arteriography was required when intervention appeared necessary (Fig 3). Since portions of these vessels are oriented relatively perpendicular to the axially directed (carotid system) flow detected with 2-D TOF techniques, weak or absent subclavian or siphon flow signals can occur. Similarly for near-occlusion, faint cervical and intracranial ICA flow signals resulting from low velocity, "trickle" flow associated with greater than 95% stenosis may lack detail necessary to define a surgically accessible length of ICA disease on MRA images and arteriography may be necessary.

To further assess the adequacy of preoperative imaging methods for CEA planning, perioperative outcome was compared between patients requiring MRA after inadequate duplex scanning and a concurrent cohort undergoing CEA solely on the basis of a technically adequate duplex scan. Adequacy of preoperative imaging was indirectly measured by the need for intraoperative technical adjustments to anticipated (planned) or unexpected (unplanned) anatomy. Both the overall percentage of interventions requiring technical adjustment (26%) and the percentage that were planned (71%) were greater in the MRA group than in the group undergoing CEA after duplex scanning only. The potentially more complex anatomy in the MRA group that required a secondary imaging study after duplex scanning also appears to have enabled more complete operative planning. Although combined stroke and death rates were not statistically different between MRA and duplex scanning only groups, higher overall procedural morbidity was noted in the MRA group. More complex anatomy, associated technical difficulty, and need for adjustments, and a larger proportion of patients with symptomatic disease all could contribute to the higher morbidity in the MRA group after CEA, despite apparent improved operative planning. The greater proportion of patients with symptomatic disease in the MRA group may be explained by bias toward more detailed anatomic investigation of potential emboligenic sites after hemispheric or retinal symptoms. Adverse neurologic outcome after CEA is more common in patients with symptoms (NASCET[13]) than in patients without symptoms (Asymptomatic Carotid Atherosclerosis Study[18]), and may explain at least some of the difference in morbidity between the MRA and duplex scanning only groups.

On the basis of our initial validation experience demonstrating accuracy of MRA for grading severity of ICA stenosis[11] and the ability of MRA to resolve anatomy after inadequate duplex scanning demonstrated in this study, performance of arteriography in patients with cerebrovascular occlusive disease can be minimized. We conclude that safe performance of CEA can be achieved without arteriography after indeterminate or inadequate duplex scanning when conclusive MRA defines anatomy for patient selection and operative planning.

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